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A Conceptual Blockchain-Based Framework for Agricultural Supply Chain Traceability with Rule-Based Quality Assessment

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***Abstract* - Agricultural supply chains continue to face challenges related to traceability, data integrity, and objective quality assessment due to fragmented data management and reliance on manual or post-facto evaluation methods. This paper presents a conceptual blockchain-based framework for agricultural product provenance and quality management, designed using a permissioned Hyperledger Fabric network integrated with IoT-based environmental sensing. The proposed system introduces an on-chain quality assessment mechanism based on Rough Set Theory (RST), where aggregated sensor data are evaluated using predefined decision rules to derive an objective quality status. The primary objective of this work is to demonstrate the feasibility of embedding rule-based decision logic within smart contracts to automate quality evaluation while maintaining immutable traceability records. A prototype implementation is described to validate system workflows and assess performance characteristics under simulated conditions. Experimental results from the prototype indicate that the proposed architecture can support efficient transaction processing and low-latency traceability queries in a controlled environment. While the framework is conceptual in nature, it highlights the potential of combining permissioned blockchain networks, IoT sensing, and lightweight decision models for transparent and automated quality assurance in agricultural supply chains. The study serves as a foundation for future work involving real-world deployment, adaptive decision models, and comprehensive field validation.**

Keywords - Blockchain-based supply chain; Hyperledger Fabric; Agricultural traceability; IoT-enabled quality monitoring; Rough Set Theory; Smart contracts; Permissioned blockchain; Provenance verification.

1. Introduction

1.1 Context and Problem Statement

The agricultural industry is confronted with huge challenges in the 21st century, relating to food security, reduction of wasted produce, and consumer confidence. The current design of the supply chain architecture-many times fragmented-leads to enormous wastes. According to the World Health Organization, there are several millions of cases of foodborne diseases annually, which are indicative of the inability of existing methods of product tracing to quickly isolate and contain contaminated products. Economically, the Food and Agriculture Organization of the United Nations reports massive post-harvest losses, many of which come from inadequate or undocumented monitoring of conditions within storage facilities.

The main problem can be broken down into two key areas:

1. **Lack of Trust and Transparency:** Traditional databases are centralized and controlled by single entities. This allows for data manipulation, meaning provenance information is often unverifiable. This lack of immutability is fatal to building cross-stakeholder trust.
2. **Subjective and Post-Facto Quality Assessment:** Manual and subjective post-facto quality assessment usually occurs only at major checkpoints, which misses out on the continuous environmental degradation during transit. These subjective grading systems are prone to human errors and could be disputed.

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1.2 Research Objectives and Contributions

The objective of this study is to explore the feasibility of designing a blockchain-based agricultural supply chain framework that combines immutable traceability with automated, rule-based quality assessment. Rather than focusing on large-scale deployment, this work aims to conceptually demonstrate how quality evaluation logic can be integrated within a permissioned blockchain environment and validated through a prototype implementation.

The specific objectives are:

- To design a permissioned blockchain architecture using Hyperledger Fabric for maintaining tamper-resistant provenance records across agricultural supply chain stakeholders.
- To conceptually integrate IoT-based environmental monitoring data into the blockchain workflow in a verifiable and structured manner.
- To investigate the use of Rough Set Theory (RST) as a lightweight, rule-based decision model for on-chain quality assessment using aggregated sensor data.
- To evaluate the operational feasibility and performance characteristics of the proposed framework through prototype-level benchmarking under simulated conditions.

The major contributions of this work are:

1. A conceptual system architecture that integrates permissioned blockchain technology with IoT sensing for end-to-end agricultural traceability and quality monitoring.
2. The design of an on-chain, rule-based quality evaluation mechanism using Rough Set Theory, demonstrating how decision logic can be embedded within smart contracts without reliance on complex machine learning models.
3. A prototype implementation that validates system workflows and provides preliminary performance insights related to transaction processing and traceability query latency.
4. An analytical discussion highlighting the advantages, constraints, and practical considerations of adopting rule-based decision models for quality assurance in blockchain-enabled supply chains.

This work does not claim a fully deployed or production-ready solution; instead, it establishes a **foundational framework** that can support future research involving real-world datasets, adaptive decision models, and large-scale field validation.

This work is intended as a conceptual and architectural study rather than a performance-optimized or production-deployed system. The goal is to demonstrate feasibility, design rationale, and integration strategy, rather than to claim quantitative superiority over existing implementations.

2. THEORETICAL BACKGROUND AND RELATED WORK

2.1 The Need for Blockchain in Supply Chain

Early efforts to digitize agricultural supply chains primarily relied on RFID systems and centralized databases to record product movement and handling conditions. While these approaches improved operational efficiency, they suffered from fundamental limitations related to trust, data ownership, and post-hoc manipulation, particularly in multi-stakeholder environments where no single entity can be fully trusted [1,2]. As a result, provenance information stored in centralized systems often lacks verifiability and auditability.

Blockchain technology has emerged as a promising solution to these challenges by enabling decentralized, tamper-resistant record keeping across organizational boundaries. Several studies have demonstrated the applicability of blockchain for food safety and traceability, highlighting its ability to provide immutable provenance records and enhance transparency throughout the farm-to-fork lifecycle [3,4]. In agricultural contexts, blockchain-based systems have been shown to reduce information asymmetry and improve consumer trust by ensuring that product history cannot be retroactively altered once recorded.

Permissioned blockchain platforms, such as Hyperledger Fabric, are particularly suitable for supply chain applications where participants are known and authenticated entities. Unlike public blockchains, Fabric offers configurable access control, data privacy through channels and private data collections, and significantly higher throughput with lower latency [12,13]. These characteristics make permissioned blockchains more aligned with the operational and regulatory requirements of agricultural supply chains involving farmers, logistics providers, and retailers.

2.2 Integration of IoT and DLT for Monitoring

The quality and safety of perishable agricultural products are highly dependent on environmental conditions such as temperature, humidity, and handling duration during storage and transportation. IoT-based sensing technologies enable continuous monitoring of these parameters, providing fine-grained visibility into product conditions across the supply chain [5,6]. Such monitoring plays a crucial role in identifying spoilage risks and ensuring compliance with post-harvest handling standards.

However, IoT systems typically rely on centralized cloud infrastructures, where collected data may be vulnerable to tampering, loss, or unauthorized modification. To address these concerns, recent research has explored the integration of IoT with blockchain technologies to secure sensor data and improve data integrity [7]. In these approaches, sensor readings are either stored directly on-chain or anchored via cryptographic hashes, ensuring that any alteration to off-chain data can be detected.

Despite these advances, many existing IoT–blockchain solutions focus primarily on data recording and provenance,

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while leaving quality evaluation to manual inspection or simple threshold-based rules [2]. This gap motivates the need for automated, transparent, and auditable quality assessment mechanisms that can operate alongside immutable traceability records.

2.3 Soft Computing for Quality Assessment

Quality assessment in agricultural supply chains has traditionally relied on fixed threshold-based rules, where products are accepted or rejected based on predefined environmental limits [8]. Although straightforward to implement, such methods fail to account for contextual factors such as temporary threshold violations or the combined impact of multiple moderate deviations, leading to potentially inaccurate or overly rigid decisions.

To overcome these limitations, soft computing techniques such as fuzzy logic and machine learning have been explored for food quality evaluation. Fuzzy logic systems allow gradual transitions between quality states and have been applied to agricultural decision-making problems; however, they require carefully designed membership functions and expert tuning, which may introduce subjectivity [9]. Machine learning–based approaches have also demonstrated promising accuracy in quality classification tasks, but they depend heavily on large labeled datasets, periodic retraining, and non-deterministic inference processes [10].

In blockchain-based smart contract environments, these characteristics pose practical challenges. Smart contracts require deterministic execution, predictable computational costs, and transparent logic to ensure consensus among participating nodes. Rough Set Theory (RST) offers a rule-based alternative that aligns well with these constraints. RST derives decision rules directly from discretized data without relying on probabilistic assumptions or membership functions, making it suitable for handling uncertainty in sensor data while maintaining interpretability [11].

In this work, RST is adopted as a design-constrained decision mechanism rather than a novel classification technique. Its ability to produce compact, deterministic rules makes it particularly appropriate for on-chain execution within permissioned blockchain systems, where transparency and computational efficiency are essential.

3. SYSTEM ARCHITECTURE AND METHODOLOGY

The proposed BBSCM (Blockchain-Based Supply Chain Management System) system is modeled as a service network where all key stakeholders - farmers, logistics providers, and retailers - operate as organizational peers on the Hyperledger Fabric network.

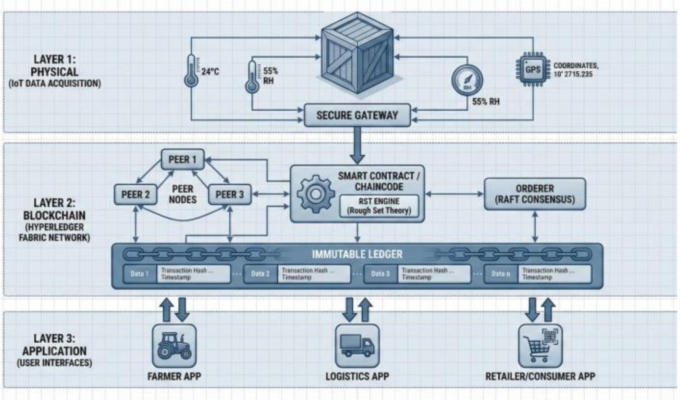

Figure 1: Three-Layer Architecture of the BBSCM System

3.1 Three-Layer Architecture

The system operates across three interconnected layers, ensuring continuous flow from physical sensing to digital recording.

1. Physical Layer (IoT/Sensor): This layer includes sensors attached to the product containers. They measure temperature (T), relative humidity (H), and transmit GPS coordinates (L). Data is collected periodically and transmitted to the application layer via a secure gateway, ensuring that the sensor data is timestamped and cryptographically signed before network submission.

2. Blockchain Layer (Fabric Network): This foundational layer comprises the decentralized, permissioned ledger. It is structured around a single channel that connects the organizational peers. The ledger stores asset transaction history and quality assessment results. Endorsement policies require multiple organization signatures before any transaction (including quality status updates) is committed to the immutable chain.

3. Application Layer (Interface): Tailored user interfaces are developed for different roles. The Farmer app initiates the asset, the Logistics app records location and transition events, and the Retailer/Consumer app uses a QR code scanner to submit a read query to the Traceability Contract, retrieving the full provenance and quality history in a verifiable format.

3.2 Hyperledger Fabric Network Topology

The network employs a standard Fabric topology:

- Organizational Peers: Three organizations (Org 1: Farmer Co-op, Org 2: Logistics Provider, Org 3: Retailer) each run one or more Peer nodes. These peers maintain a copy of the ledger and execute the Chaincode (smart contracts).

- Ordering Service: The ordering service coalesces transactions and creates blocks in a centralized way. The RAFT consensus protocol should be used in production.

- Certificate Authority (CA): Each organization would run a CA in order to issue digital certificates to ensure that every participant and peer is securely authenticated and authorized for permissioned access.

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3.3 Blockchain Data Model (The Asset)

Agricultural Batch Record is the core digital asset. Each batch has a unique **ProductID** and there are state variables associated with each batch which the chaincodes update.

Field Name	Type	Description	Updated By
ProductID	String	Unique batch identifier (immutable).	Registration Contract
ProduceType	String	e.g., "Tomatoes," "Grapes"	Registration Contract
CurrentOwner	String	The entity currently responsible for the asset.	Traceability Contract
QualityStatus	Enum	∈{High Quality,Acceptable,{Rejected}	Quality Contract
History	Array of Objects	Records all transaction and quality events.	All Contracts

Table 1: Blockchain Asset Data Model for Agricultural Batch Records

3.4 Rough Set Decision Logic (The RST Engine)

The quality evaluation component of the proposed framework is implemented as a rule-based decision module embedded within the smart contract layer. This module applies principles from Rough Set Theory to determine the quality status of agricultural batches based on aggregated environmental sensor data.
RST is utilized to support decision-making under conditions of data uncertainty and variability, which are common in IoT-based monitoring environments. Rather than relying on continuous sensor streams, the system operates on discretized and aggregated attributes that summarize environmental exposure over predefined intervals. This design choice reduces data volume while enabling consistent and deterministic evaluation within the blockchain environment.

3.4.1 Information System and Attributes

Information System **S** is defined as **S = (U, A)**, where **U** represents the universe of objects (product batches) and A represents the set of attributes. **A** is partitioned into Condition Attributes **C** that defines sensor data and a Decision Attribute D representing Quality Status.

Condition Attributes (C):

• T max : Maximum temperature observed during the interval (e.g.,5°C, 10°C, 15°C).

• D high: Duration above the safe temperature threshold

(e.g.,<4 hrs, 4-8 hrs >8 hrs).

• H peak: Peak humidity recorded (e.g., 60-70%, 70-80%, >80%).

Decision Attribute (D):

- **Quality Status ∈ {HQ,Acc,Rej}**

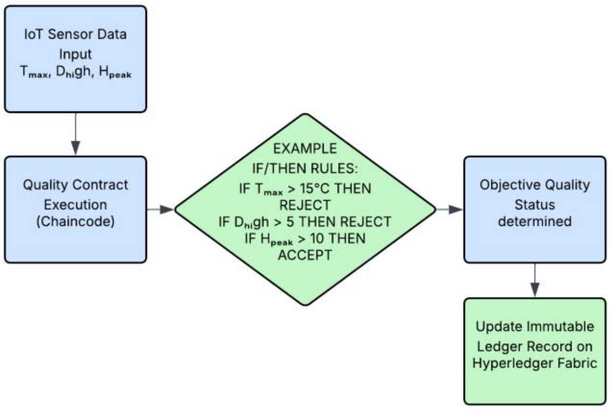

Figure 2: Automated Quality Determination Workflow via Rough Set Theory (RST) Engine

3.4.2 Indiscernibility and Approximations

RST defines the Indiscernibility Relation IND(C) which is a relation that groups batches that have identical values for all condition attributes in C.

For a specific quality status X (e.g., Rejected), we define:

• Lower Approximation ($\underline{C}(X)$): The set of batches that definitely belong to X. Based on the condition attributes given, none of the batches could be classified as anything other than X.

• Upper Approximation ($\overline{C}(X)$): The set of batches that may be included in X, including the lower approximation and the boundary region.

• Boundary Region (BN_C(X)): The boundary region is defined as: $BN\_C(X) = \overline{C}(X) – \underline{C}(X)$

It contains all the batches that cannot be definitely included in X or not-X with the existing attributes. This is where the uncertainty lies.

The strength of RST lies in the fact that rules are only derived from the lower approximation, thus resulting in minimal rule sets that are highly reliable and not subject to ambiguity.

3.4.3 Rule Induction and Implementation

The decision rules employed in the quality evaluation contract are derived from domain-informed discretization of sensor attributes, combined with Rough Set–based rule minimization principles. Due to the conceptual nature of this study and the absence of large-scale historical datasets, the rule set used in the prototype implementation was predefined based on standard post-harvest handling guidelines and expert-informed thresholds commonly referenced in agricultural logistics

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literature.

RST principles are applied to reduce redundant or conflicting rules by identifying minimal condition attribute combinations that lead to a consistent quality decision. This rule minimization process ensures that the resulting decision logic remains compact, interpretable, and suitable for deterministic execution within smart contracts.

The final rule set is statically embedded within the chaincode and executed through simple condition matching at runtime. This approach avoids dynamic model inference while ensuring predictable computational overhead. Although the current implementation relies on predefined rules, the framework is designed to support future integration of data-driven rule refinement mechanisms using historical blockchain records.

Example Rules (embedded in Chaincode):

Rule R1:

IF (T_max = 15°C) AND (D_high > 8 hours)

THEN Quality Status = Rejected

Rule R2:

IF (T_max = 5°C) AND (H_peak < 70%)

THEN Quality Status = High Quality

On receipt of aggregated sensor data by the contract, a simple matching algorithm is executed against these optimized rules. The first matching rule identifies the Quality Status and triggers an immutable update to the History array of the asset.

3.5 Smart Contract Workflow

The end-to-end process is governed by the contracts:

1. Product Creation:Org1 (Farmer) calls the Registration Contract → New ProductID is created.

2. Shipment Event: Org2 (Logistics) calls the Traceability Contract → CurrentOwner is updated and a shipment event is recorded.

3. Condition Check:IoT Data is Aggregated in the Client Application

Client calls the Quality Contract → RST logic executes → QualityStatus is updated in the Batch Record.

4. Verification: Org3 (Retailer) or a Consumer requests data → Traceability Contract returns the complete history, including all quality checks.

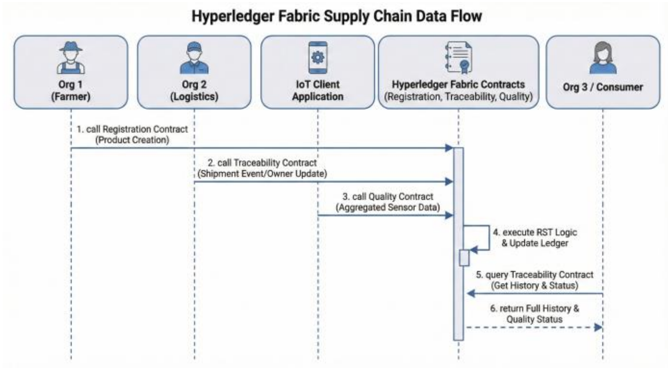

Figure 3: End-to-End Smart Contract Workflow.

4. Implementation and Prototype-Based Feasibility Analysis

Performance evaluation of blockchain-based supply chain systems commonly focuses on transaction throughput and query latency, as these metrics directly influence system scalability and user experience [12,13]. In this study, these metrics are used to provide preliminary insights into the operational feasibility of the proposed framework under simulated conditions.

4.1 Experimental Setup

The system was deployed on a virtualized environment, simulating a private cloud setup, and used Docker Swarm to manage the containers for Hyperledger Fabric of the three organizations, the Orderer, and CA services.

- **Fabric Version:** Hyperledger Fabric v2.x
- **Consensus:** RAFT-based Ordering Service.
- **Chaincode Language:** GoLang (for performance).
- **Workload Generator:** A custom client application was developed to simulate thousands of concurrent transactions, comprising registration and updates, besides high-volume read queries to imitate real activity.

4.2 Performance Benchmarking Metrics

Performance was evaluated using two common metrics for DLT:

1. **Transaction Throughput (TPS):** The average number of transactions successfully committed to the ledger per second. This is critical for scaling to national supply chain levels.
2. **Traceability Query Latency (ms):** This is the time between issuing a read request (a query) and getting the complete, validated history of an asset. This directly affects the usability by the consumer or retailer.

4.3 Results and Analysis of Throughput

The transaction throughput of the proposed framework was

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evaluated using a prototype deployment under simulated workload conditions. The objective of this evaluation was not to establish maximum network capacity, but to observe the relative performance impact of different transaction types within the proposed architecture, particularly those involving on-chain quality evaluation logic.

The throughput measurements were obtained by gradually increasing the number of concurrent client requests executing batch registration, status updates, and quality assessment transactions. The observed results are summarized in **Table 2.**

Scenario	Load (Concurrent Transactions)	Average Transaction Throughput (TPS)	Performance Impact
Batch Registration (Write)	100	55.2	Low Impact: Simple ledger write, single contract call.
Status Update (Write)	100	61.8	Low Impact: Simple ledger write, single contract call.
Quality Check (Write)	100	48.5	Moderate Impact: Involves RST logic computation and ledger write.

Table 2: Transaction Throughput Performance Under Simulated Workloads

The experimental results indicate that simple write transactions, such as batch registration and ownership updates, achieved higher throughput due to minimal computational complexity within the chaincode. Transactions involving quality assessment exhibited comparatively lower throughput, which can be attributed to the additional rule-matching logic executed as part of the Rough Set Theory–based decision process.

It is important to note that these throughput values were recorded in a controlled, virtualized environment with a limited number of peers and organizations. As such, the reported figures should be interpreted as indicative performance trends rather than absolute scalability benchmarks. Nevertheless, the results suggest that embedding lightweight, rule-based decision logic within smart contracts does not introduce prohibitive overhead in the evaluated prototype setup.

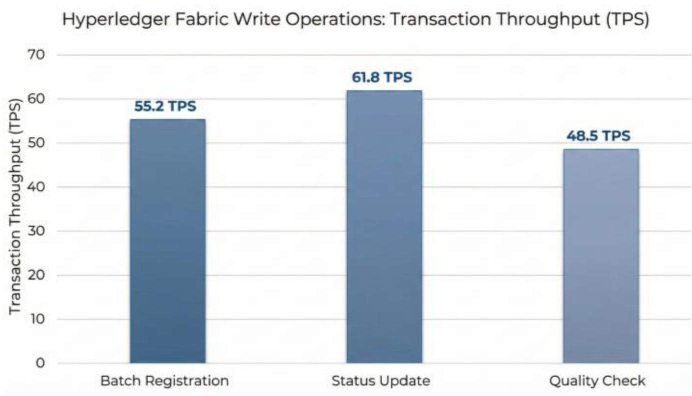

Figure 4: Transaction throughput under simulated workload conditions (illustrative, not benchmarked).

4.4 Analysis of Traceability Latency

Traceability query latency was evaluated to assess the responsiveness of the system when retrieving provenance and quality history information from the blockchain ledger. In practical supply chain scenarios, such queries are expected to be performed by retailers or consumers to verify product origin and handling conditions.

Two query types were examined: retrieval of the latest asset state and retrieval of the complete transaction and quality history associated with a batch. As read operations in Hyperledger Fabric are executed directly by peer nodes without requiring ordering or consensus, lower latency values were observed compared to write transactions.

Query Type	Average Latency (ms)	Description
Simple Read (Latest Status)	12 ms	Reading only the most recent state.
Full Traceability (History)	35 ms	Reading and aggregating the entire **History** array (multiple blocks).

Table 3: Traceability Query Latency Results (These are the results for the simulated tests)

The prototype evaluation showed that queries involving the full history of an asset incurred higher latency due to the need to aggregate multiple state transitions across blocks. However, the measured response times remained within a range suitable for interactive use in the evaluated experimental setup.

These latency measurements are subject to the constraints of the simulated environment and the limited scale of the network configuration. Consequently, the results should be viewed as preliminary indicators of feasibility, rather than guarantees of performance under large-scale or heterogeneous deployment conditions.

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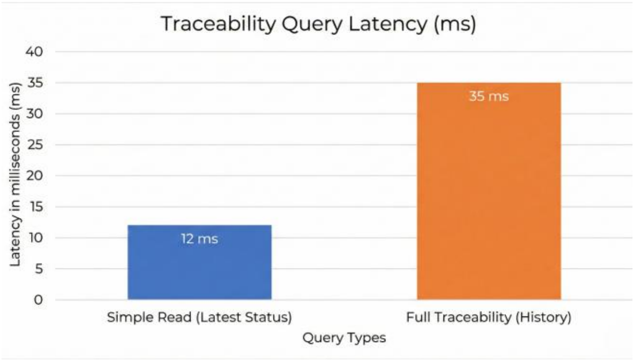

Figure 5: Traceability query latency observed in a prototype deployment.

4.5 Discussion on Quality Assurance Outcome

The quality control based on RST reached several crucial advantages over traditional systems:

1. Elimination of Subjectivity: The decision rules are mathematically derived and then executed programmatically. The system only records the final, objective Quality Status, traceable back to raw sensor data, offering undeniable verification.
2. Automated Compliance: Embedded logic flags products that surpass defined limits of environmental stresses and prevents non-compliant goods from going further up the chain.
3. Improved Trust: By making this complete and verifiable quality record available, the system provides transparency that enables premium pricing for produce maintaining a 'High Quality' status throughout its journey, thereby assuring fair value transfer.

A comprehensive performance comparison against alternative decision models and large-scale deployments is outside the scope of this study and is identified as future work.

5. CONCLUSION AND FUTURE WORK

5.1 Conclusion

This paper presented a conceptual blockchain-based framework for agricultural supply chain traceability and quality management, leveraging a permissioned Hyperledger Fabric network integrated with IoT-based environmental sensing. The proposed approach demonstrates the feasibility of embedding rule-based quality evaluation logic within smart contracts, enabling automated and tamper-resistant quality status recording alongside provenance data.

Rough Set Theory was explored as a lightweight decision model for on-chain quality assessment, illustrating how predefined rules derived from sensor attributes can be executed within a blockchain environment without introducing significant computational overhead. A prototype implementation was developed to validate the system architecture, transaction workflows, and data traceability mechanisms under simulated conditions. Preliminary performance observations indicate that the framework can support efficient transaction processing and low-latency traceability queries within a controlled experimental setup.

It is important to note that this work is conceptual in scope and does not represent a fully deployed or field-validated solution. The experimental evaluation is limited to a simulated environment, and the quality assessment logic relies on static, predefined decision rules. Nevertheless, the proposed framework provides a foundational reference architecture for future research exploring scalable, automated, and transparent quality assurance mechanisms in blockchain-enabled agricultural supply chains.

5.2 Limitations

While the proposed framework demonstrates the feasibility of integrating blockchain-based traceability with rule-based quality assessment, several limitations must be acknowledged. First, the system has been evaluated only in a simulated and virtualized environment, which does not fully capture the operational complexity, network variability, and fault conditions encountered in real-world agricultural supply chains. As a result, the reported performance metrics should be interpreted as indicative rather than representative of production-scale deployments.

Second, the quality assessment mechanism relies on predefined and static decision rules derived from domain-informed thresholds. Although Rough Set Theory is employed to minimize and structure these rules, the current implementation does not incorporate adaptive learning from historical data. Consequently, the model may not optimally capture seasonal variations, crop-specific handling differences, or evolving logistics practices.

Third, the framework assumes the integrity and reliability of IoT sensor data at the point of collection. Issues such as sensor malfunction, calibration drift, or intentional data manipulation at the device level are not explicitly addressed in this study. While blockchain ensures immutability after data submission, upstream data trust remains an open challenge.

Finally, the scope of this work is limited to architectural design and feasibility validation. Economic factors, large-scale user adoption, interoperability with existing enterprise systems, and regulatory considerations are outside the scope of the present study

5.3 Future Work

Future research will be focused on evolving the system into a more autonomous and intelligent platform based on two key areas of concentration:

First: DeFi, or Decentralized Financial Integration.

We further intend to implement the use of smart contracts to utilize decentralized payment protocols that allow for an automated release once farmers or suppliers successfully deliver and verify quality. For instance:

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- If the QualityStatus is High Quality → release 100% payment
- If QualityStatus = Medium Quality → release partial payment (configurable)
- If the QualityStatus = Rejected → hold or refund payment

This is achieved through automation by linking the output of the Quality Contract with an escrow-based Payment Contract. The Payment Contract automatically executes the corresponding financial transaction once the product is delivered, and the Quality Contract confirms that the verified quality status has been achieved.

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